

# MSSM Higgs Searches at the Tevatron and the LHC: Impact of Different Benchmark Scenarios

*Sven Heinemeyer, University of Zaragoza*

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1. Motivation and theory
2. MSSM Higgs bosons at the Tevatron
3. MSSM Higgs bosons at the LHC
4. Conclusions

## 1. Motivation and theory

MSSM Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

physical states:  $h^0, H^0, A^0, H^\pm$

Goldstone bosons:  $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta)$$

## Contrary to the SM:

$m_h$  is not a free parameter

MSSM tree-level bound:  $m_h < M_Z$ , excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta m_h^2 \sim G_\mu m_t^4 \ln \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of  $m_h$ , Higgs couplings  $\Rightarrow$  test of the theory

LHC:  $\Delta m_h \approx 0.2$  GeV

ILC:  $\Delta m_h \approx 0.05$  GeV

$\Rightarrow m_h$  will be (the best?) electroweak precision observable

## Upper bound on $m_h$ in the MSSM:

“Unconstrained MSSM”:

$M_A$ ,  $\tan \beta$ , 5 parameters in  $\tilde{t}$ – $\tilde{b}$  sector,  $\mu$ ,  $m_{\tilde{g}}$ ,  $M_2$

$$m_h \lesssim 135 \text{ GeV}$$

for  $m_t = 172.7 \text{ GeV}$

(including theoretical uncertainties from unknown higher orders)  
⇒ observable at the LHC

Obtained with:

*FeynHiggs*

[S.H., W. Hollik, G. Weiglein '98, '00, '02]

[T. Hahn, S.H., W. Hollik, G. Weiglein '03, '04]

[www.feynhiggs.de](http://www.feynhiggs.de)

→ all Higgs masses, couplings, BRs (easy to link, easy to use :-)

## The decoupling limit:

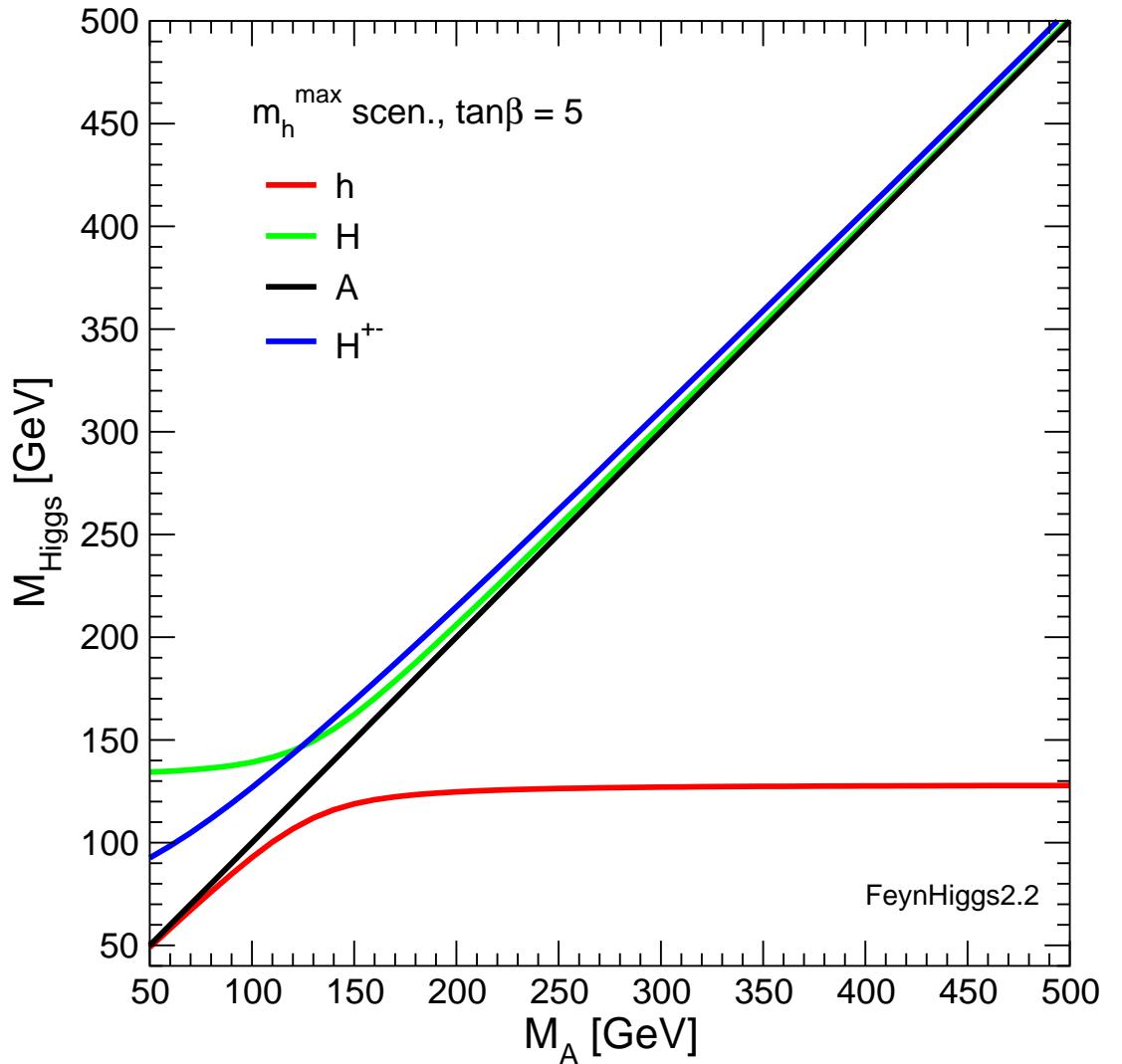
For  $M_A \gtrsim 150$  GeV:

The **lightest** MSSM Higgs is  
**SM-like**

The **heavy** MSSM Higgses:

$$M_A \approx M_H \approx M_{H^\pm}$$

of course there are exceptions . . .



## $\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ( $X_t = A_t - \mu/\tan\beta$ ,  $X_b = A_b - \mu\tan\beta$ ):

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M_{\tilde{t}_R}^2 + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$

$$\mathcal{M}_{\tilde{b}}^2 = \begin{pmatrix} M_{\tilde{b}_L}^2 + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M_{\tilde{b}_R}^2 + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m_{\tilde{b}_1}^2 & 0 \\ 0 & m_{\tilde{b}_2}^2 \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large  $\tan\beta$ )

soft SUSY-breaking parameters  $A_t, A_b$  also appear in  $\phi$ - $\tilde{t}/\tilde{b}$  couplings

$$SU(2) \text{ relation} \Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$$

$\Rightarrow$  relation between  $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

## Search for the lightest MSSM Higgs boson:

Situation is more involved due to many SUSY parameters

→ investigate benchmark scenarios:

- Vary only  $M_A$  and  $\tan\beta$
- Keep all other SUSY parameters fixed

### 1. $m_h^{\max}$ scenario:

→ obtain conservative  $\tan\beta$  exclusion bounds ( $X_t = 2 M_{\text{SUSY}}$ )

### 2. no-mixing scenario

→ no mixing in the scalar top sector ( $X_t = 0$ )

### 3. small $\alpha_{\text{eff}}$ scenario

→  $h b \bar{b}$  coupling  $\sim \sin \alpha_{\text{eff}} / \cos \beta$  can be zero:  $\alpha_{\text{eff}} \rightarrow 0$ :  
main decay mode vanishes, important search channel vanishes

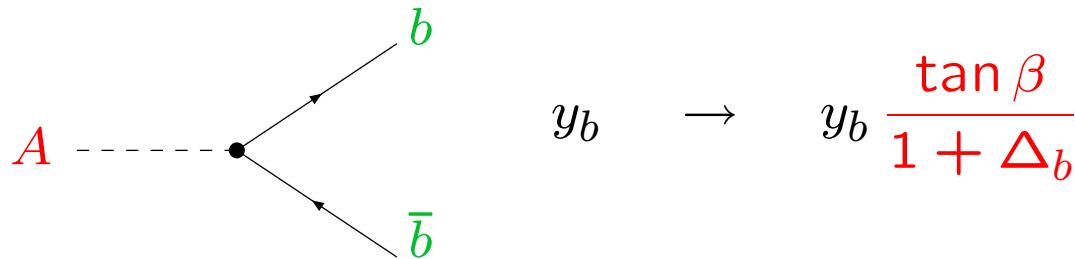
### 4. gluophobic Higgs scenario

→  $h gg$  coupling is small: main LHC production mode vanishes

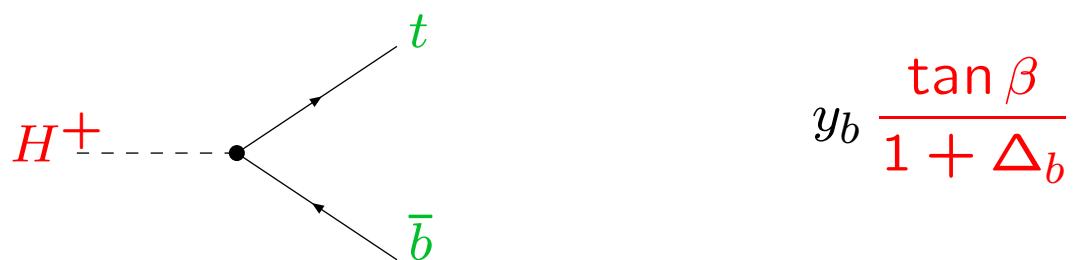
[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

## Search for the heavy MSSM Higgs bosons:

Additional enhancement factors compared to the SM case:



At large  $\tan \beta$ : either  $H \approx A$  or  $h \approx A$



$$\begin{aligned} \Delta_b &= \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan \beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \\ &+ \frac{\alpha_t}{4\pi} A_t \mu \tan \beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) \end{aligned}$$

⇒ other parameters enter ⇒ strong  $\mu$  dependence

## Suggestion for new benchmark scenarios:

[M. Carena, S.H., C. Wagner, G. Weiglein '05]

→ investigate benchmark scenarios:

- Vary only  $M_A$  and  $\tan \beta$  (large!)
- Keep all other SUSY parameters fixed

- Vary in addition  $\mu$ :  $\mu = \pm 1000, \pm 500, \pm 200$  GeV  
(if perturbativity allows)

1.  $m_h^{\max}$  scenario:

→ obtain conservative  $\tan \beta$  exclusion bounds ( $X_t = 2 M_{\text{SUSY}}$ )

$A_t$  large  $\Rightarrow$  large  $\mathcal{O}(\alpha_t)$  contribution to  $\Delta_b$

2. no-mixing scenario

→ no mixing in the scalar top sector ( $X_t = 0$ )

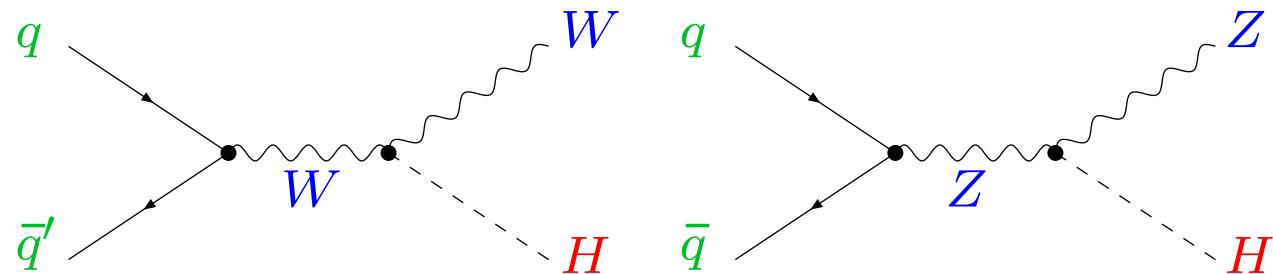
$A_t$  small  $\Rightarrow$  small  $\mathcal{O}(\alpha_t)$  contribution to  $\Delta_b$

$\Rightarrow$  large difference to  $m_h^{\max}$  scenario

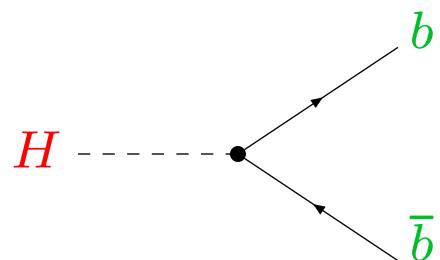
## 2. MSSM Higgs bosons at the Tevatron

Search for a SM-like Higgs:

Dominant production processes:

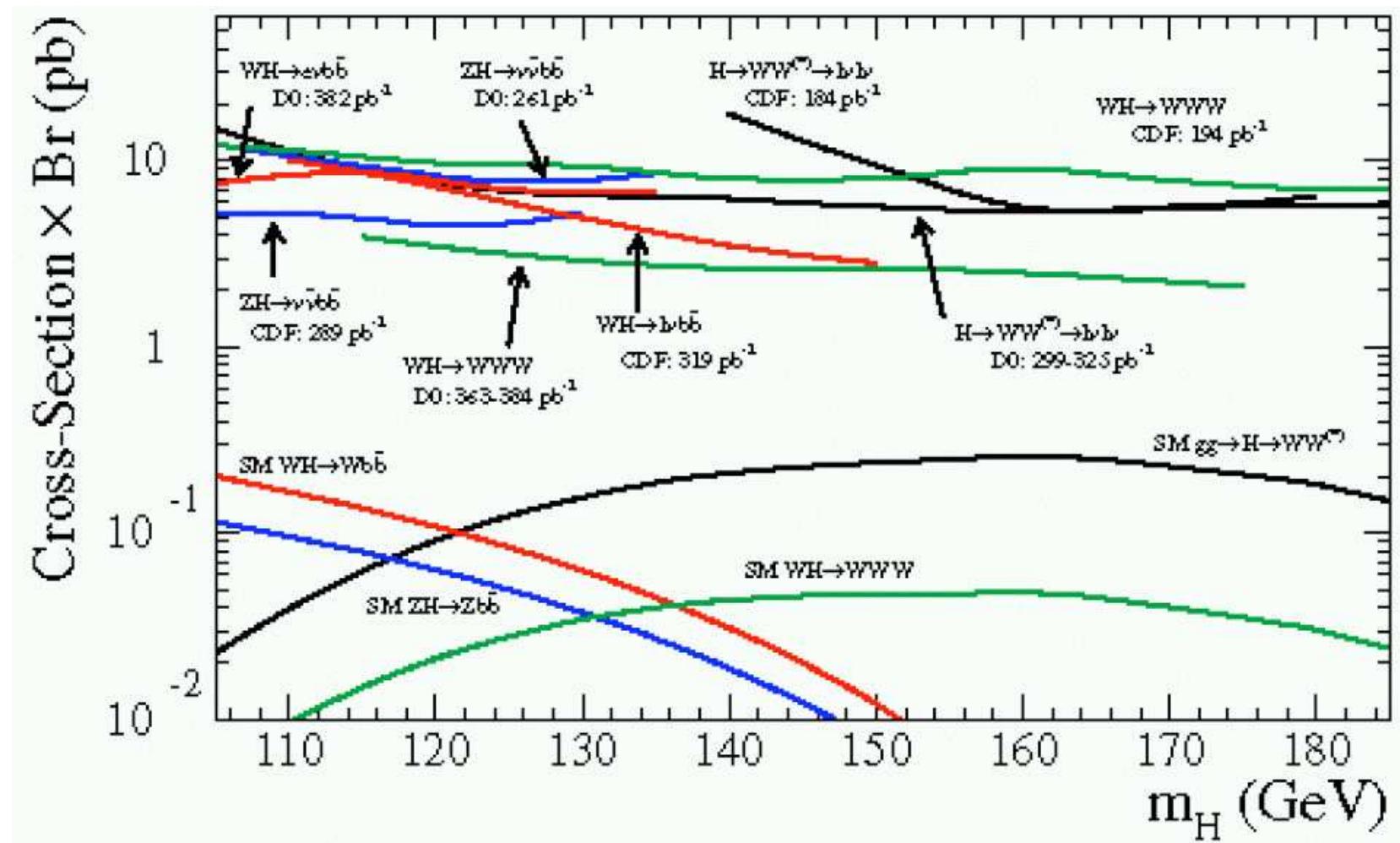


Dominant decays:  $H \rightarrow b\bar{b}$



## Current status of SM Higgs search:

[*CDF, D0 '05*]



Can they close the gap?

## Possible problem in SUSY:

$$h \rightarrow b\bar{b}$$

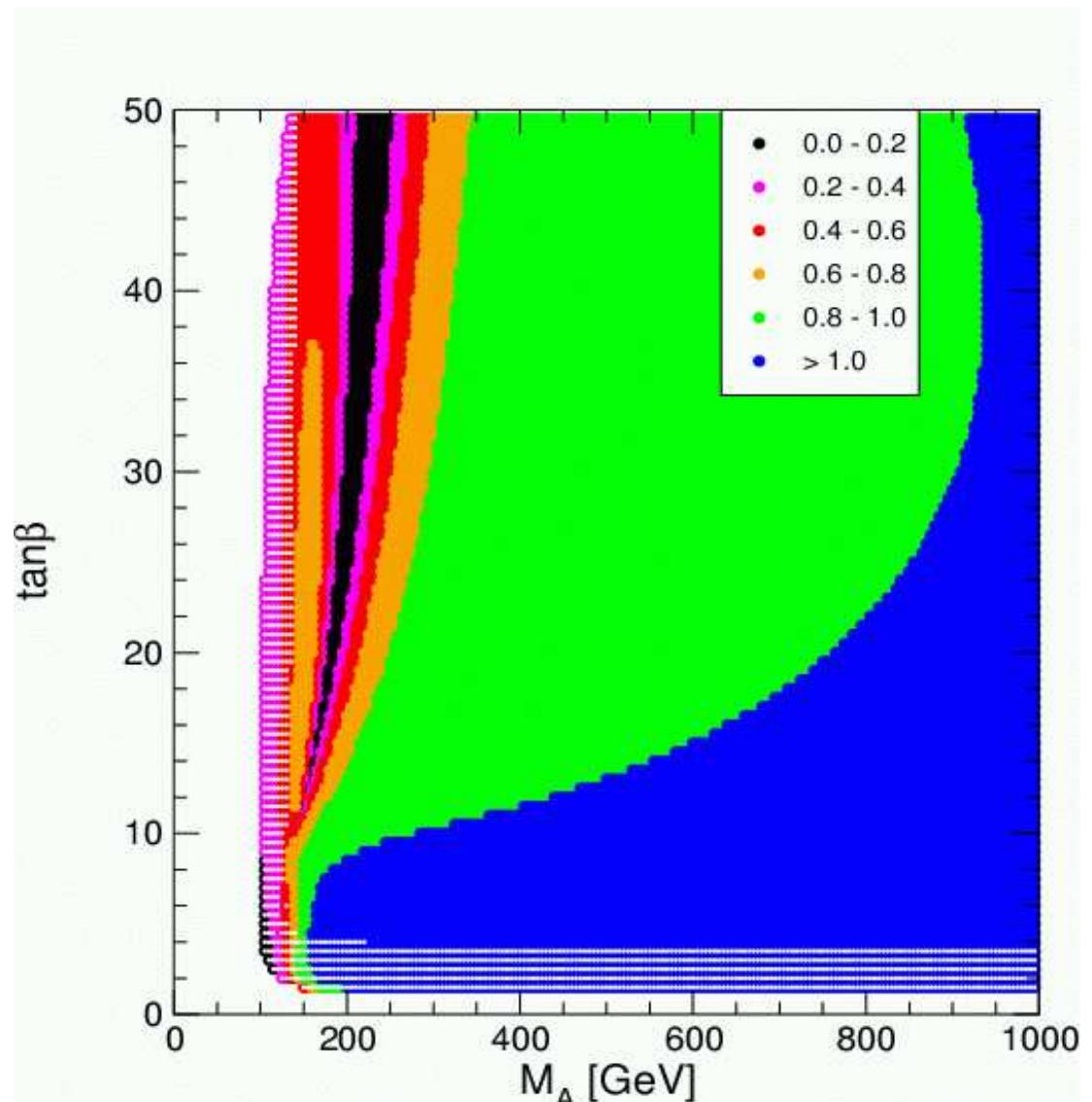
can be **strongly suppressed**

→ “Small  $\alpha_{\text{eff}}$  scenario”

[*M. Carena, S.H., C. Wagner,  
G. Weiglein '02*]

⇒ Strong suppression of  
 $h \rightarrow b\bar{b}$  possible,  
up to  $M_A \lesssim 350$  GeV

(not realized in  
mSUGRA/CMSSM, GMSB,  
AMSB, . . . )



## “Heavy” MSSM Higgs searches:

Search modes:

$$\begin{aligned} b\bar{b} \rightarrow \phi b\bar{b}, \quad \phi = h, H, A \\ p\bar{p} \rightarrow \phi \rightarrow \tau^+ \tau^-, \quad \phi = h, H, A \end{aligned}$$

Strong enhancement compared to the SM:

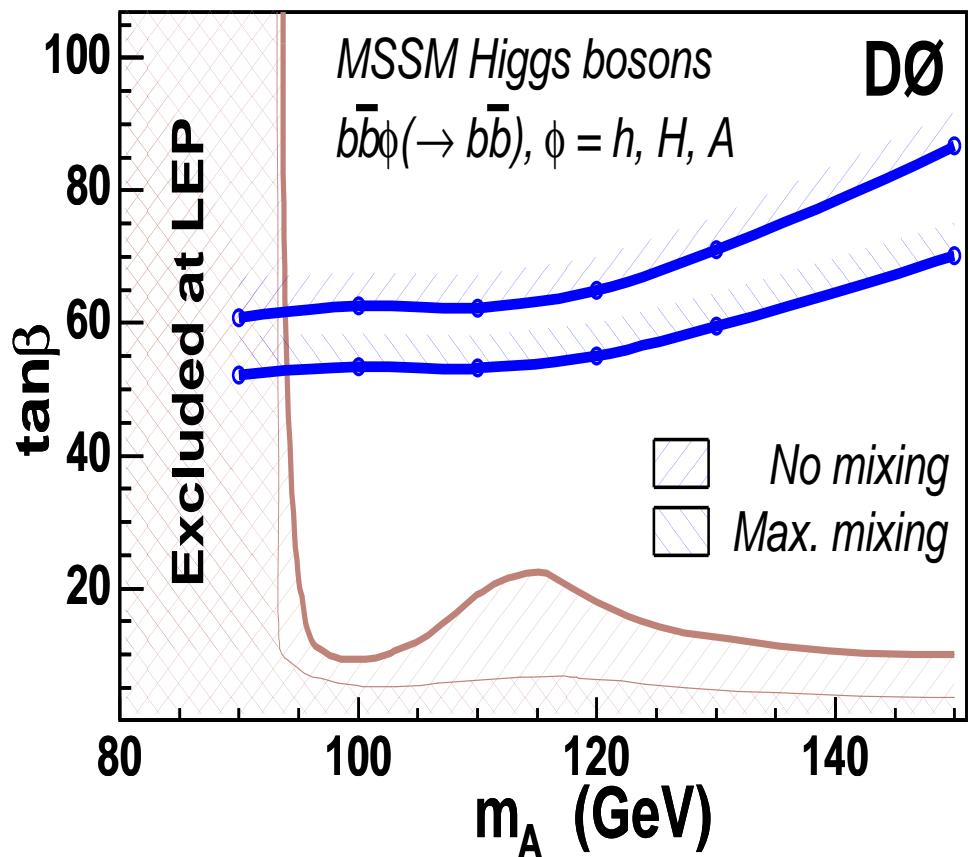
$$\sigma(b\bar{b}A) \times \text{BR}(A \rightarrow b\bar{b}) \simeq \sigma(b\bar{b}A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{9}{(1 + \Delta_b)^2 + 9}$$

$$\sigma(gg, b\bar{b} \rightarrow A) \times \text{BR}(A \rightarrow \tau^+ \tau^-) \simeq \sigma(gg, b\bar{b} \rightarrow A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2 + 9}$$

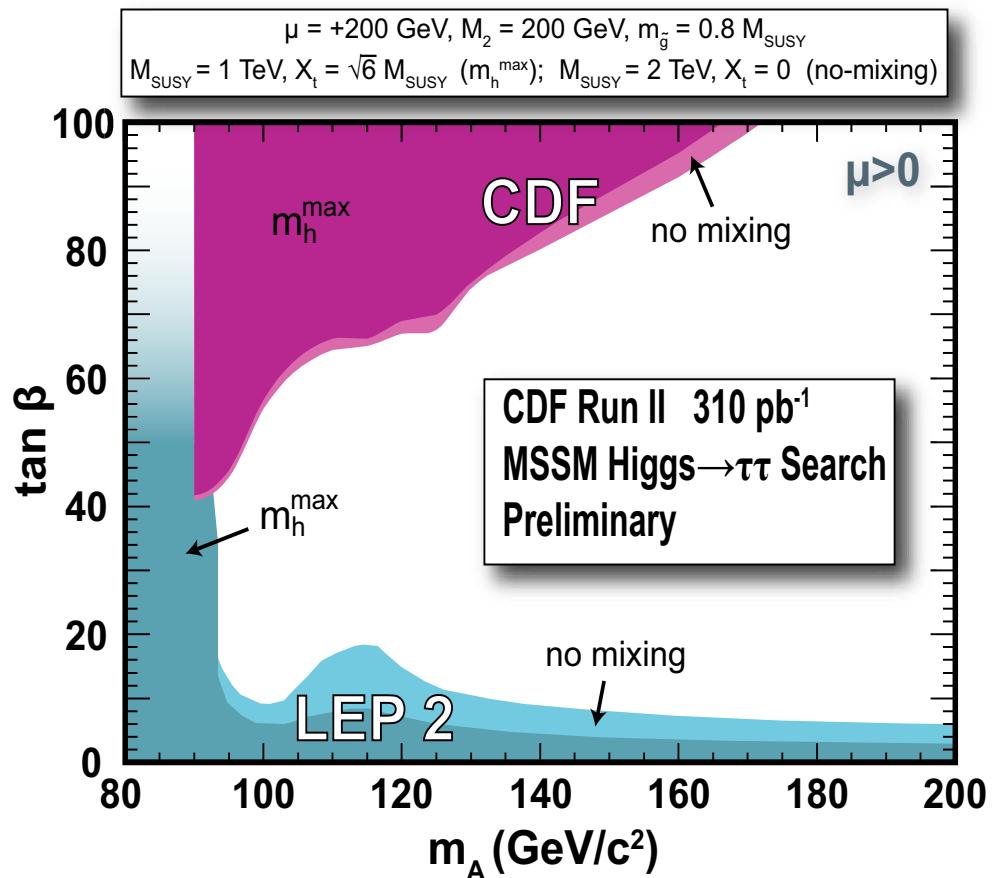
$$\begin{aligned} \Delta_b &= \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan \beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \\ &+ \frac{\alpha_t}{4\pi} A_t \mu \tan \beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) \end{aligned}$$

Either  $H \approx A$  or  $h \approx A \Rightarrow$  another factor of 2

Existing Tevatron data allows bounds on SUSY parameter space:



[D0 '05]

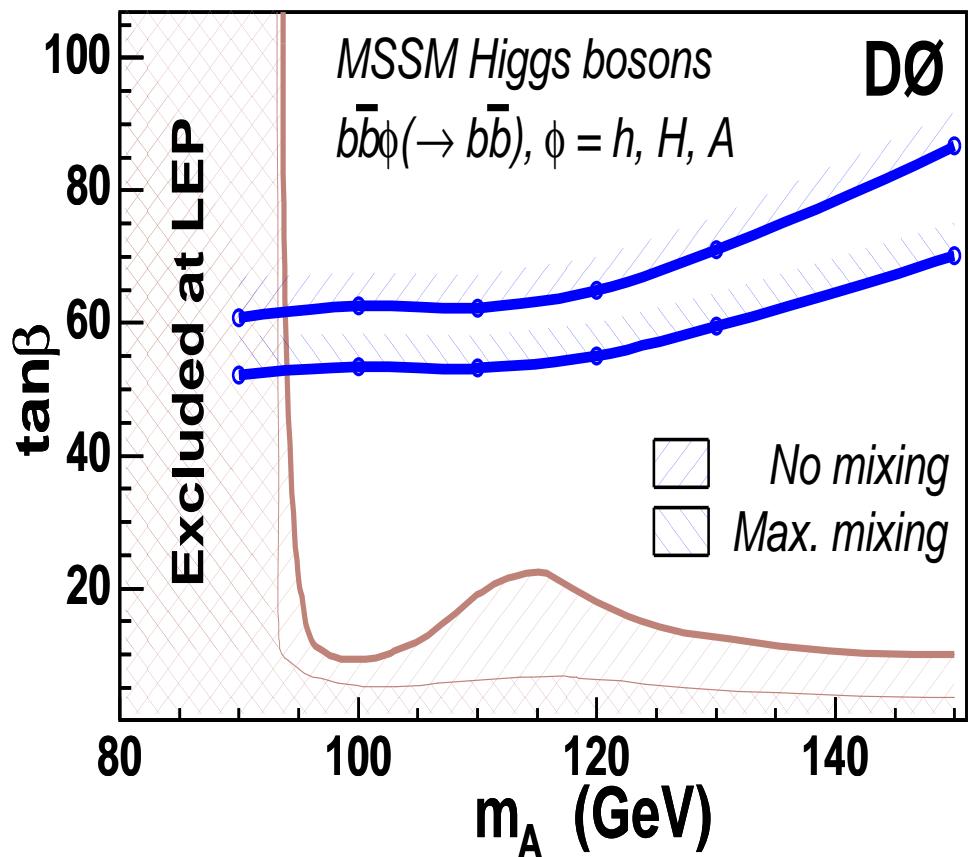


[CDF '05]

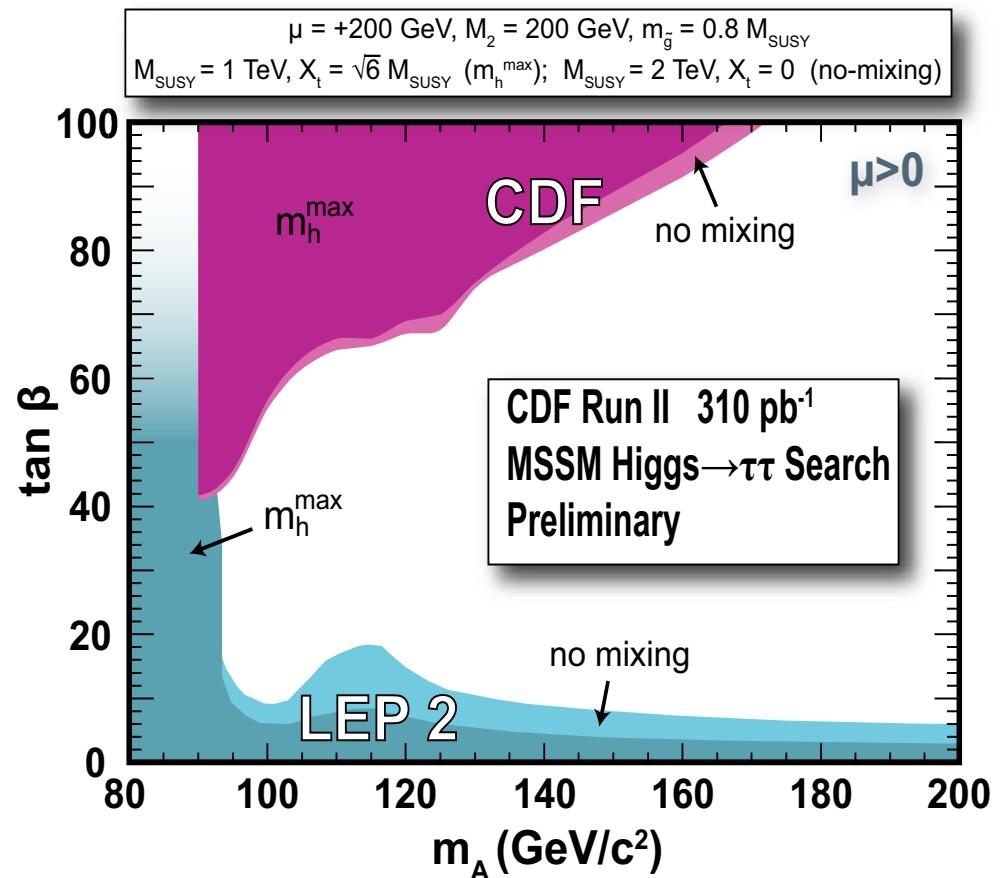
⇒ Bounds on the MSSM parameter space for low  $M_A$ , high  $\tan \beta$ :

$\tan \beta \approx 50$  excluded for  $M_A \approx 100 \text{ GeV}$

Existing Tevatron data allows bounds on SUSY parameter space:



[D0 '05]



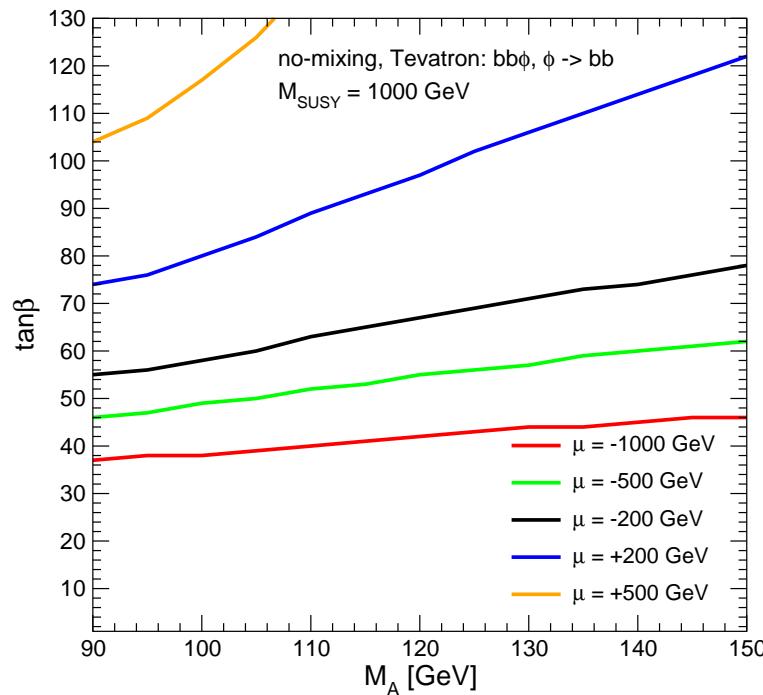
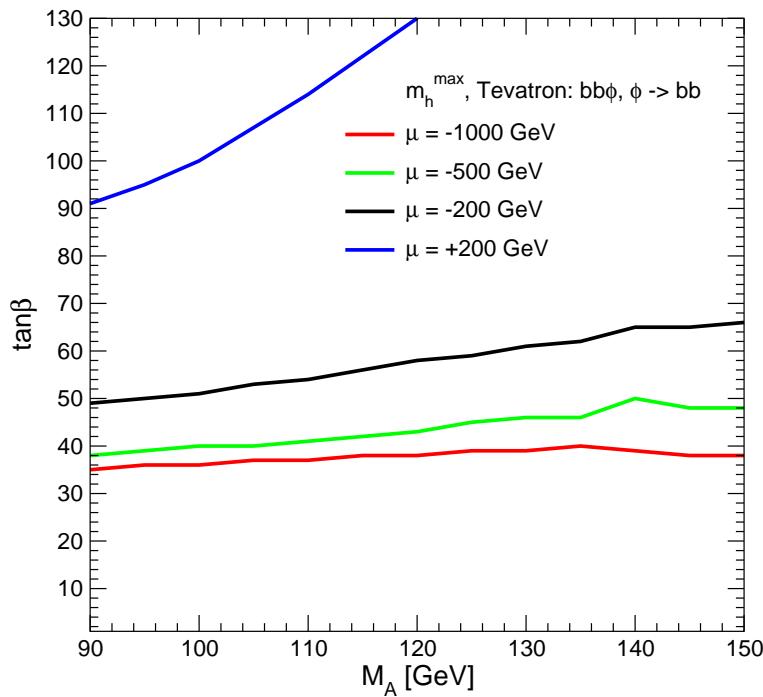
[CDF '05]

⇒ Bounds on the MSSM parameter space for low  $M_A$ , high  $\tan \beta$ :

$\tan \beta \approx 50$  excluded for  $M_A \approx 100 \text{ GeV}$   
in certain benchmark scenarios!  $\mu$  fixed!

## Dependence of Tevatron bounds from $b\bar{b}\phi, \phi \rightarrow b\bar{b}$ on $\mu$ :

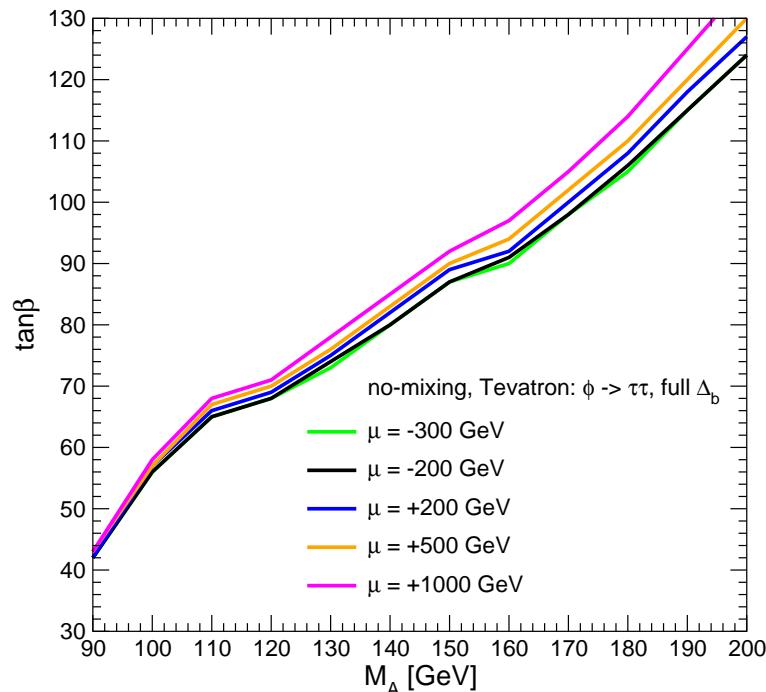
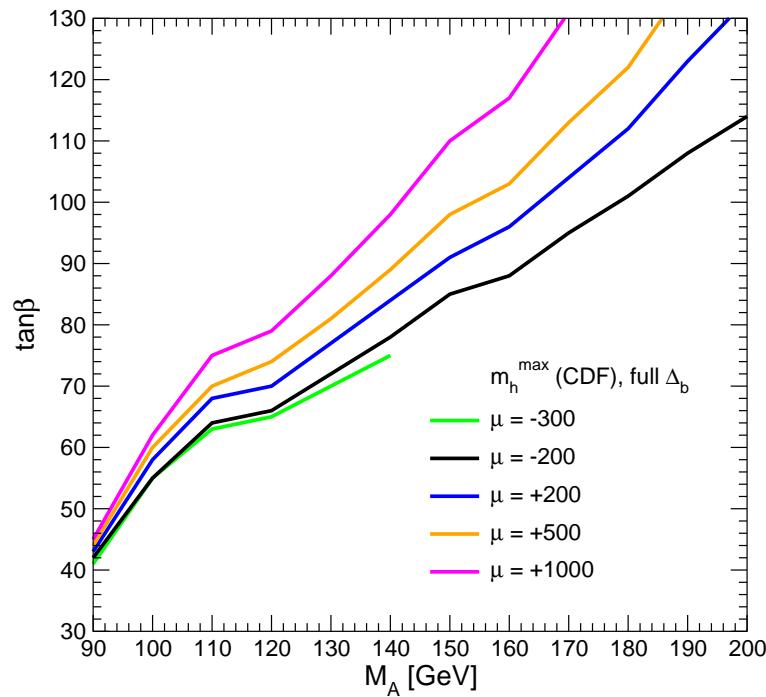
[M. Carena, S.H., C. Wagner, G. Weiglein '05]



- ⇒ strong variation with the sign and absolute value of  $\mu$
- ⇒ much stronger or weaker bounds possible
- no bounds for  $\mu \gtrsim 200$  GeV  
(positive  $\mu$  preferred by  $(g-2)_\mu$ )

## Dependence of Tevatron bounds from $p\bar{p} \rightarrow \phi, \phi \rightarrow \tau^+\tau^-$ on $\mu$ :

[M. Carena, S.H., C. Wagner, G. Weiglein '05]



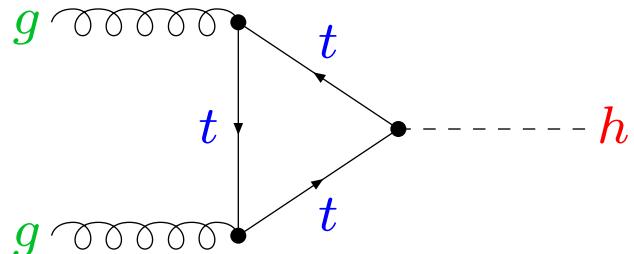
- ⇒ less strong variation with the sign and absolute value of  $\mu$   
(→ numerical compensations in production and decay)
- ⇒ still much stronger or weaker bounds possible  
strong dependence on benchmark scenario

### 3. MSSM Higgs bosons at the LHC

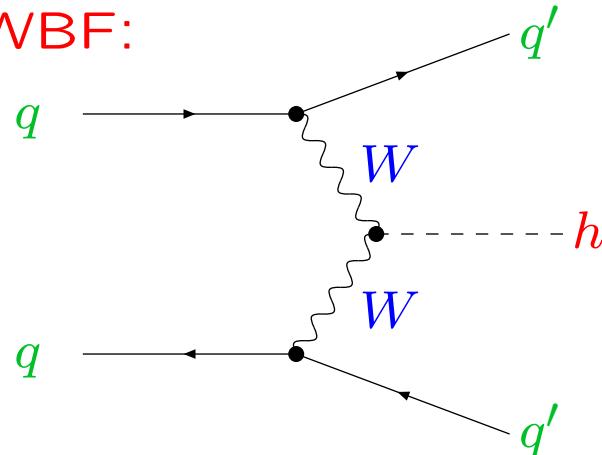
Search for a SM-like Higgs:

Important production channel at the LHC:

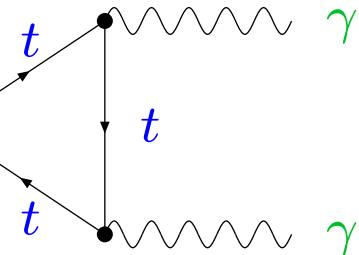
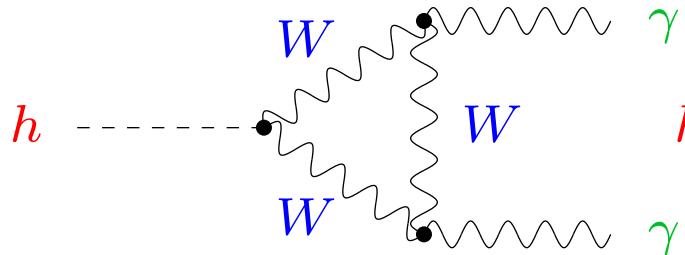
Gluon-Fusion:



WBF:

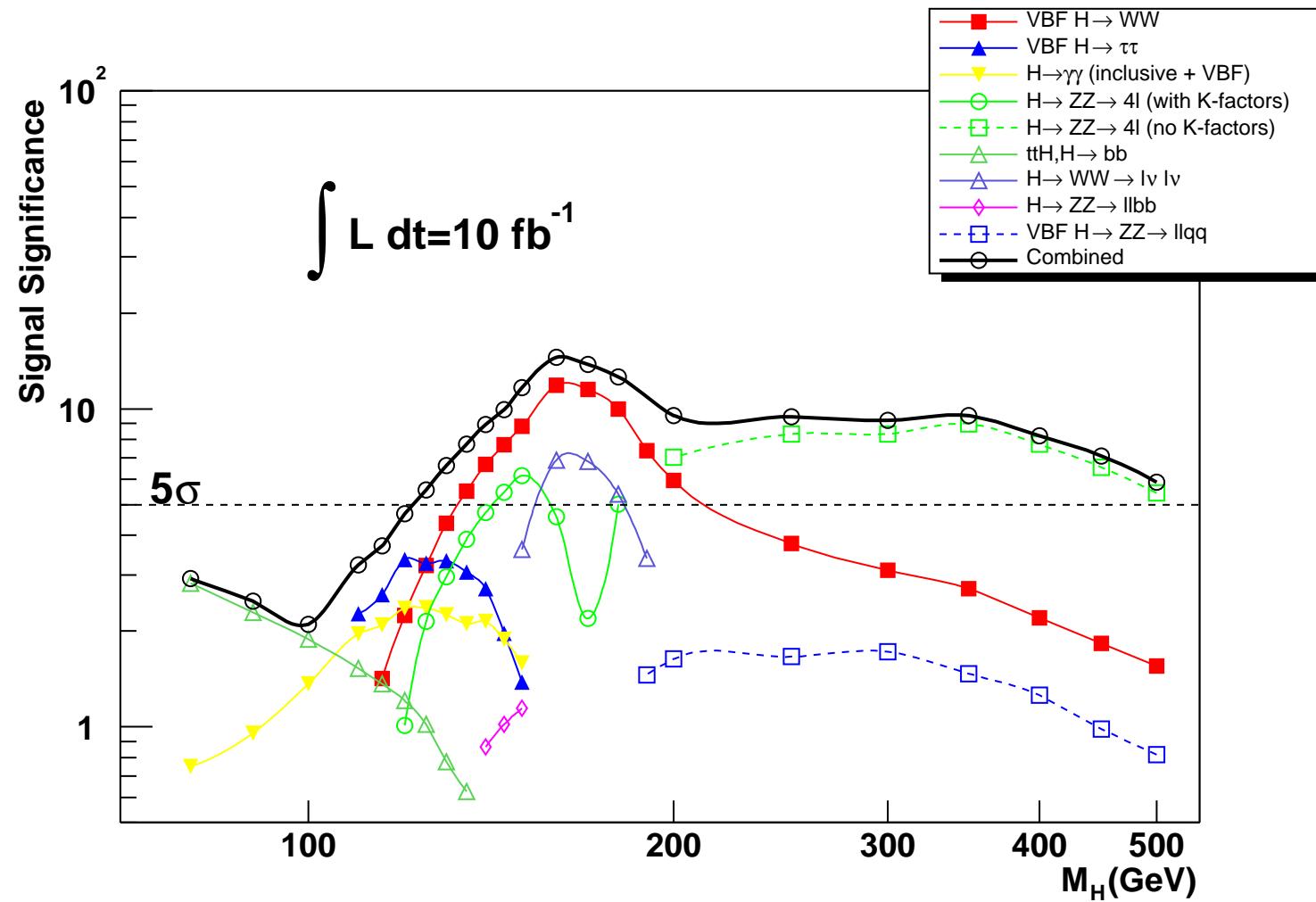


Important decay for Higgs mass measurement:



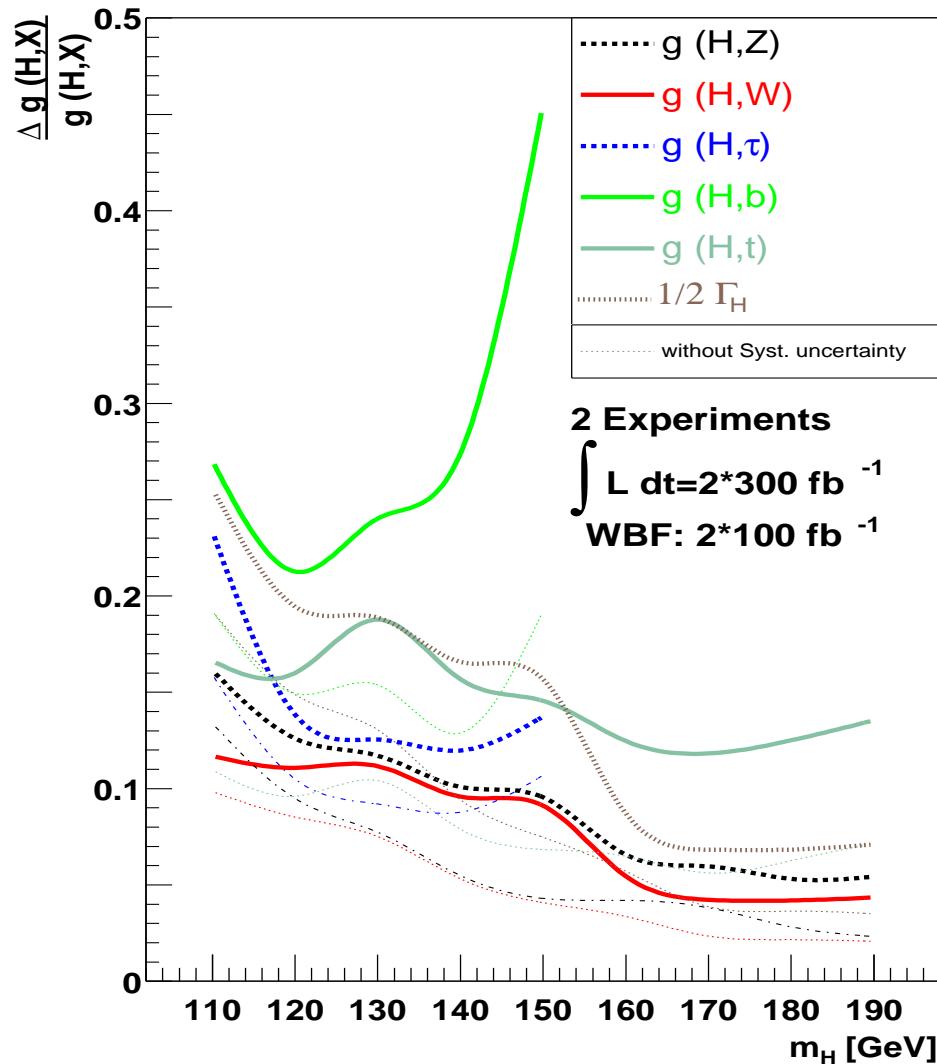
## SM Higgs search at the LHC: $\Rightarrow$ full parameter accessible, also at CMS :-)

[ATLAS '05]



## Higgs coupling determination at the LHC:

[M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04]



With mild theory assumptions:

- typical accuracies of **10-15%** for  $m_H \leq 150$  GeV
- **5%** accuracies for  $HVV$  couplings above  $WW$  threshold
- Systematic errors contribute up to half of the total error, especially at high luminosity

## Possible problem in SUSY:

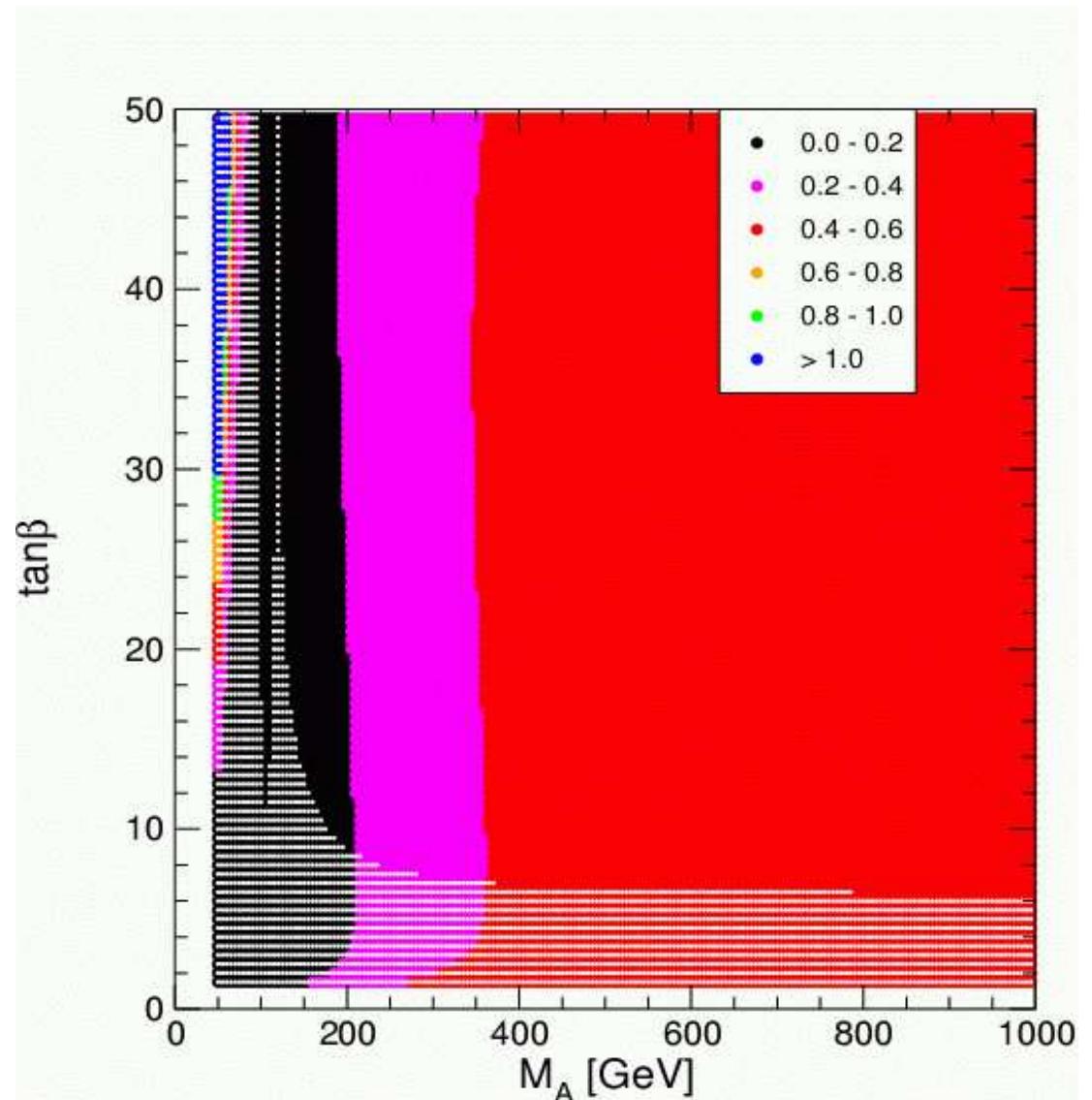
$$gg \rightarrow h \rightarrow \gamma\gamma$$

can be **strongly suppressed**

→ “gluophobic Higgs scenario”

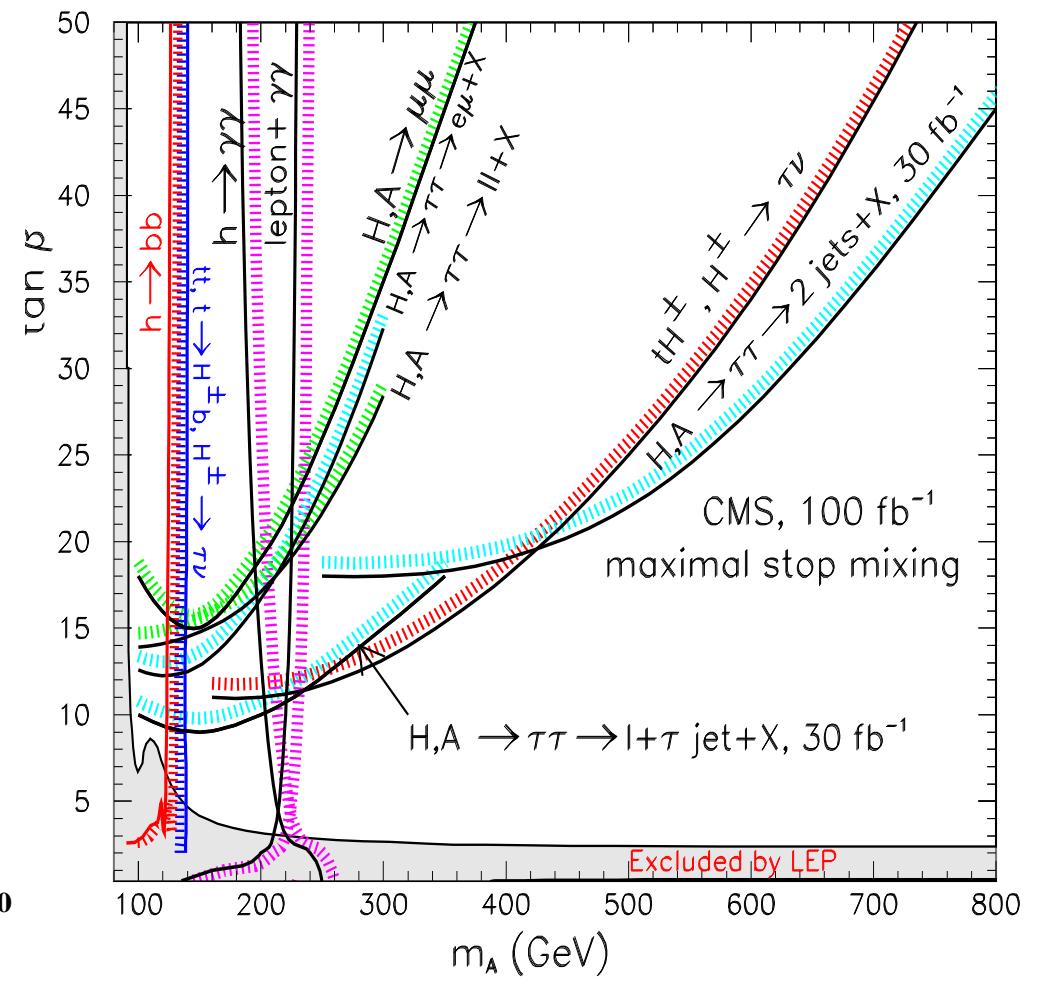
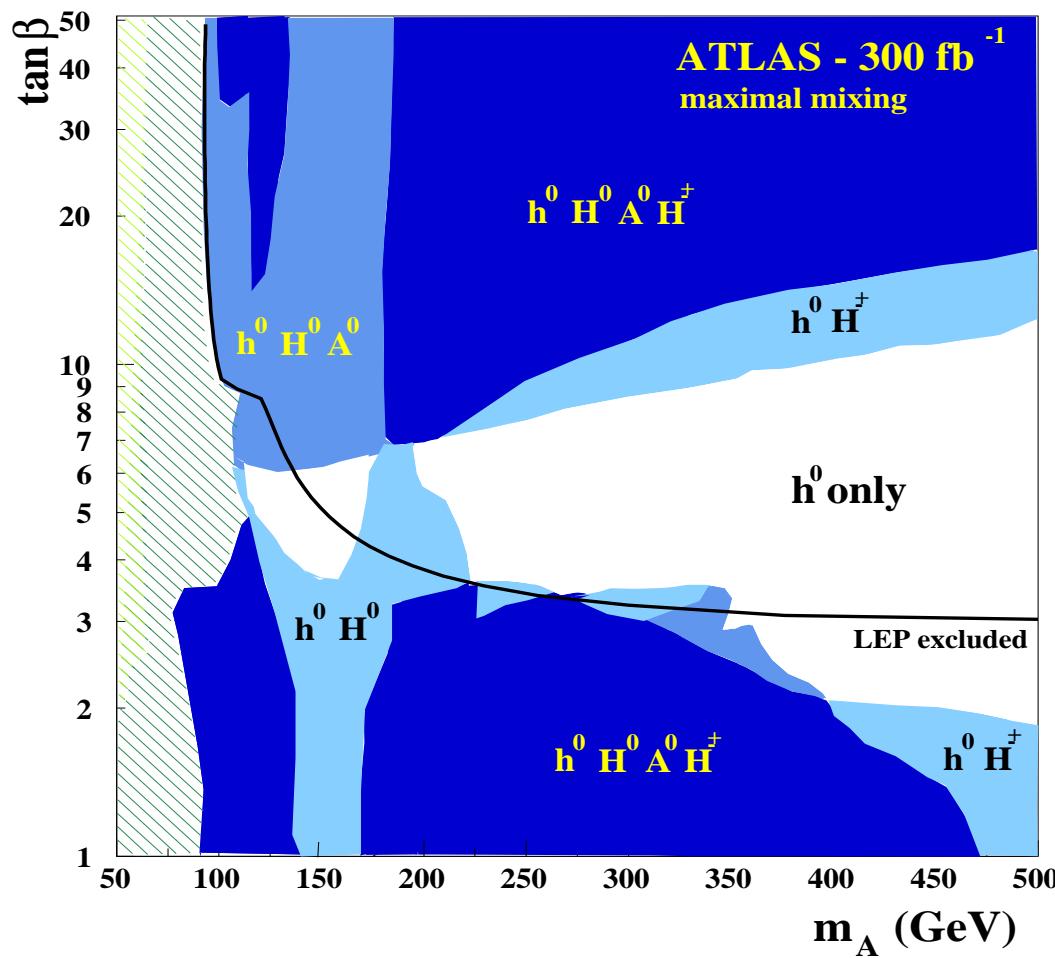
[*M. Carena, S.H., C. Wagner,  
G. Weiglein '02*]

⇒ Strong suppression of  
 $gg \rightarrow h \rightarrow \gamma\gamma$  possible  
over the whole parameter space



## “Heavy” MSSM Higgs searches:

MSSM Higgs discovery contours in  $M_A$ – $\tan\beta$  plane  
 $(m_h^{\max}$  benchmark scenario): [ATLAS '99] [CMS '03]



## Most powerful search modes for heavy MSSM Higgs bosons:

$$\boxed{b\bar{b} \rightarrow H/A \rightarrow \tau^+\tau^- + X \\ pp \rightarrow tH^\pm + X, \ H^\pm \rightarrow \tau\nu_\tau}$$

Enhancement factors compared to the SM case:

$$H/A : \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{\text{BR}(H \rightarrow \tau^+\tau^-) + \text{BR}(A \rightarrow \tau^+\tau^-)}{\text{BR}(H \rightarrow \tau^+\tau^-)_{\text{SM}}}$$

$$H^\pm : \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \text{BR}(H^\pm \rightarrow \tau\nu_\tau)$$

⇒  $\Delta_b$  effects so far neglected by ATLAS/CMS

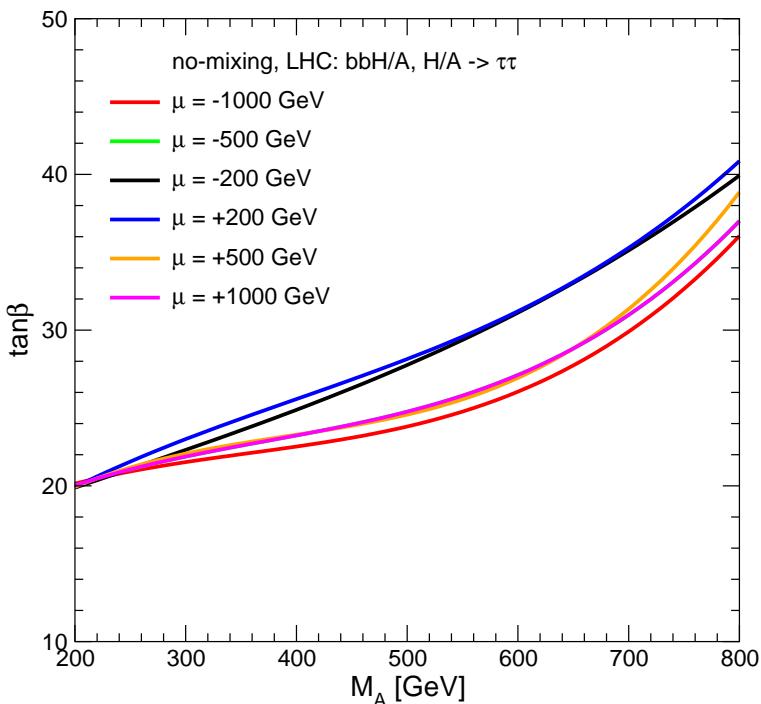
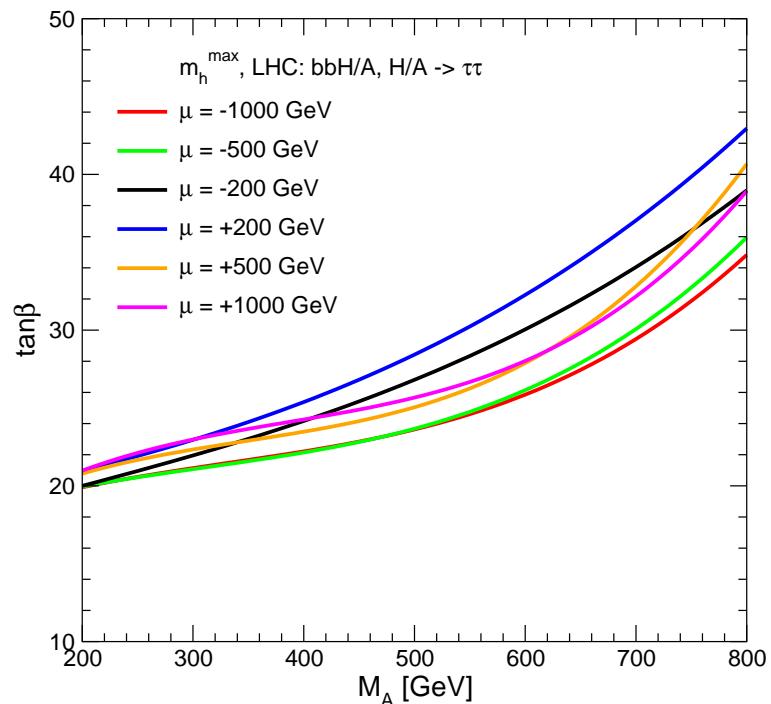
also relevant for  $\text{BR}(H/A \rightarrow \tau^+\tau^-)$ ,  $\text{BR}(H^\pm \rightarrow \tau\nu_\tau)$

also relevant: correct evaluation of  $\Gamma(H/A/H^\pm \rightarrow \text{SUSY})$

⇒ additional effects on  $\text{BR}(H/A \rightarrow \tau^+\tau^-)$ ,  $\text{BR}(H^\pm \rightarrow \tau\nu_\tau)$

## Dependence of LHC wedge from $b\bar{b} \rightarrow H/A \rightarrow \tau^+\tau^-$ on $\mu$ :

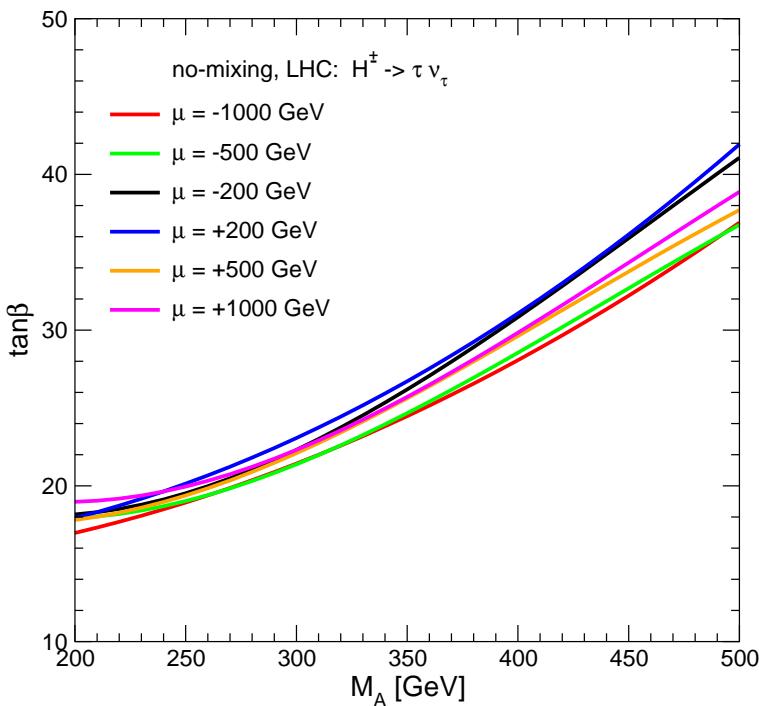
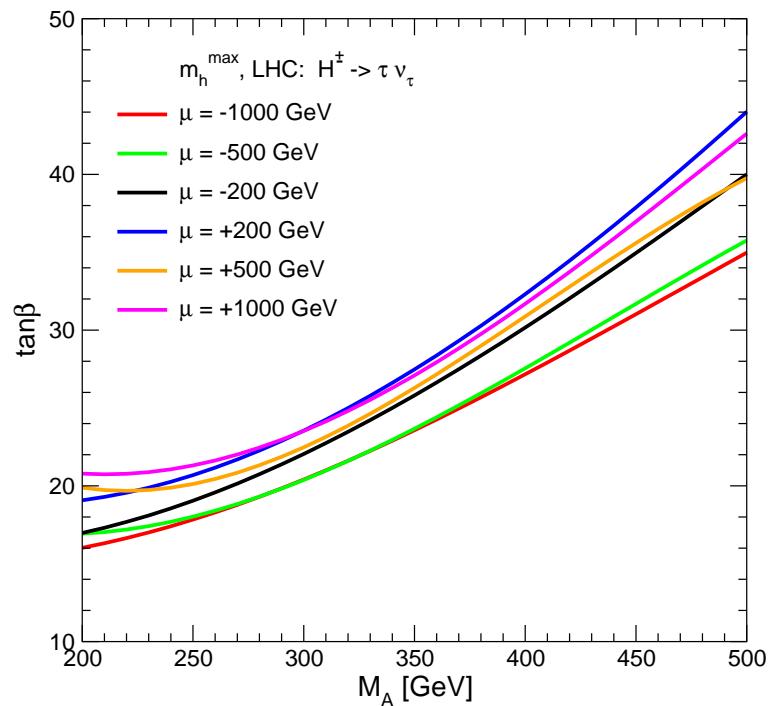
[M. Carena, S.H., C. Wagner, G. Weiglein '05]



- ⇒ non-negligible variation with the sign and absolute value of  $\mu$   
(→ numerical compensations in production and decay)
- ⇒ much stronger or weaker bounds possible  
than in existing analysis

## Dependence of the LHC wedge from $pp \rightarrow tH^\pm, H^\pm \rightarrow \tau\nu_\tau$ on $\mu$ :

[M. Carena, S.H., C. Wagner, G. Weiglein '05]



- ⇒ non-negligible variation with the sign and absolute value of  $\mu$   
(→ numerical compensations in production and decay)
- ⇒ much stronger or weaker bounds possible  
than in existing analysis

## 4. Conclusions

- MSSM: enlarged Higgs sector  
large radiative corrections all sectors enter
- SM-like Higgs searches: “old” benchmark scenarios  
“Heavy” MSSM Higgs bosons:  $y_b \times \tan\beta/(1 + \Delta_b)$   
 $\Rightarrow$  strong  $\mu$  dependence  
 $\Rightarrow$  new benchmark scenarios with  $\mu = \pm 1000, \pm 500, \pm 200$  GeV
- Tevatron is actively searching for the Higgs:  
SM: no sensitivity yet  
MSSM: current data allows to set bounds on the parameter space  
important: strong dependence on  $\mu$
- Prospects for LHC Higgs searches:  
SM: no problem; coupling determination at the 5-15% level  
MSSM: LHC wedge: only the light  $h$  can be found  
 $\rightarrow$  strong dependence on  $\mu$   
 $\Rightarrow$  applies to both channels:  $b\bar{b} \rightarrow H/A \rightarrow \tau^+\tau^-$ ,  $H^\pm \rightarrow \tau\nu_\tau$